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Management effects on soil carbon dioxide fluxes under semiarid Mediterranean conditions

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ABSTRACT

Losses of soil organic carbon (SOC) have contributed to CO_2 emissions from soils to the atmosphere and to the global climate change. We hypothesized that in semiarid agroecosystems of the Mediterranean region a shift from the traditional management system (including conventional tillage, CT, and the cereal-fallow rotation, CF) to a more conservative system, including no-tillage (NT) and continuous cropping (CC), could reduce CO_2 emissions during the cropping season. Thus, in this study, we studied the effects of tillage and cropping systems on carbon (C) inputs and soil CO_2 fluxes during three cropping seasons in three different sites of the Ebro river valley (NE Spain). C inputs ranged from 650 kg ha^{-1} to 6000 kg ha^{-1} and seasonal average CO_2 flux ranged from 0.17 to 1.65 kg ha^{-1}. Differences in rainfall led to marked differences in C inputs and soil fluxes among growing seasons. Although differences among tillage treatments were weak, CO_2 fluxes under NT were always lower. Intensification of cropping systems led to an increase of C input. A move from CT to NT together with cropping intensification are suitable practices to increase C inputs and to reduce soil CO_2 fluxes in semiarid Mediterranean agroecosystems.

Abbreviations: AG, Agramunt site; C, carbon; CC, continuous cropping system; CF, cereal-fallow rotation; CT, conventional tillage; NS, not significant; NT, no-tillage; PN, Peñaflor site; PN-CC, continuous cropping system at the Peñaflor site; PN-CF, cereal-fallow rotation at the Peñaflor site; RT, reduced tillage; SOC, soil organic carbon; SOM, soil organic matter; ST, subsoil tillage; SV, Selvanera site.

Estimates of the total soil organic carbon (SOC) of the world is close to 1500 Pg (Eswaran et al. 1993; Batjes, 1996) and about 170 Pg is contained in agricultural soils (Paustian et al., 1997). In the last two centuries, SOC losses from agricultural soils have been estimated in about 54 Pg of C (Paustian et al., 1998). These carbon (C) losses have environmental and productivity effects on agroecosystems. Thus, the mineralization of SOC has contributed to greater CO_2 emissions from soils to the atmosphere and to the global climate change (Paustian et al. 2000). In addition, the depletion of SOC has been associated with a loss of fertility and thus with a loss of productivity of the agroecosystems (Bauer and Black, 1994).

Soil CO_2 emissions respond mainly to a concentration gradient from locations with higher to lower CO_2 concentration. This process may be accelerated or restrained depending on soil micrometeorological conditions and/or soil management practices. Several studies have concluded that soil temperature is the main variable affecting soil CO_2 emissions and that soil water content has little or no effect (Hendrix et al., 1988; Bajracharya et al., 2000; Frank et al., 2006).

Soil management practices, especially tillage, modify soil profile properties and thus soil CO_2 emissions. Tillage, especially mouldboard ploughing, stimulates soil microbial activity due to greater soil aeration than conservative tillage systems such as reduced tillage or, particularly, no-tillage in which soil is not altered (Angers et al., 1993). At the same time, the breakdown of soil macroaggregates under intensive tillage systems leads to an increase on soil CO_2 emissions. Six et al. (1999) observed faster soil macroaggregate turnover in mouldboard ploughing compared with no-tillage and, thus, a greater release of labile organic matter previously protected from soil microbes within macroaggregates.

Several authors have studied the role of soil tillage practices on soil CO_2 emissions and, in addition, on the soil C budget (Alvarez et al., 1995; Franzluebbers et al., 1995; Kessavalou et al. 1998). Reducing tillage intensity may lead to a decrease of SOC losses either by enhancing C inputs returned to the field (Alvarez et al., 1995) or, in contrast, by decreasing CO_2 emissions (Kessavalou et al., 1998; Curtin et al., 2000). At the same time, intensification of cropping systems may also lead to a decrease of soil C losses due to an increase of C inputs. In the semiarid regions of the Canadian prairies, the suppression of long-fallowing in the rotation and the consequent switch from a cereal-fallow rotation to a continuous cereal system increased the soil C content due to the greater crop residues returned to the soil (Curtin et al. 2000).

Cropping intensification may also influence soil CO_2 emissions. Jacinthe et al. (2002) observed greater soil CO_2 emissions when greater amount of wheat residue was applied on soil surface probably due to a change in soil thermal properties. Curtin et al. (2000), in semiarid conditions, found greater CO_2 emissions under a continuous wheat compared with the cropped phase of a wheat-fallow rotation.

In semiarid agroecosystems of the Ebro valley (NE Spain) the cereal-fallow rotation is a widespread cropping management system aimed to increase soil water content. In this area, intensive tillage with the use of mouldboard ploughing has also been a common traditional practice. Information about the impact of these management practices on soil CO_2 emissions in the Ebro river valley region is scarce. There are some studies comparing conventional tillage (CT) and reduced tillage (RT) in other Spanish areas with similar conditions (Sánchez et al., 2002, 2003). However, in these studies, neither the impact of NT nor the intensification of cropping systems on soil CO_2 fluxes was evaluated. The objective of the present study was to determine the effects of tillage and cropping systems on C input and soil CO_2 fluxes under semiarid Mediterranean conditions. This study was carried out during three consecutive cropping seasons in three long-term experiments located along the Ebro river valley.

MATERIALS AND METHODS

Sites, Tillage and Cropping Systems

This study was conducted during three cropping seasons, from November 2002 to June 2005, at three experimental sites located in the semiarid Ebro valley region (NE Spain). Sites, from higher to lower annual precipitation, were: Selvanera (475 mm), Agramunt (430 mm) and Peñaflor (390 mm). Selected site and soil characteristics are shown in Table 1. Monthly precipitation and mean monthly air temperature recorded at the three experimental sites are presented in Table 2.

In Selvanera (SV), the cropping system consisted of a wheat (*Triticum aestivum* L.)-barley (*Hordeum vulgare* L.)-wheat-rapeseed (*Brassica napus* L.) rotation with four tillage treatments: conventional tillage (CT), subsoil tillage (ST), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of deep subsoil tillage to a depth of 40 cm in August followed by a pass with a field cultivator to a depth of 15 cm in October before sowing. The ST consisted of subsoil tillage to a depth of 25 cm in August followed by a pass with a field cultivator to a depth of 15 cm in October before sowing. The subsoiler consisted of three 4-cm wide shanks spaced 35 cm apart and the cultivator consisted of 11 flexible shanks spaced 19.5 cm apart. Unlike in the other experimental sites, mouldboard ploughing was not used in this site. The RT treatment was implemented in October with only one pass of cultivator to a depth of 15 cm.

In Agramunt, the cropping system consisted of a barley-wheat rotation with four tillage treatments: conventional tillage (CT), subsoil tillage (ST), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of a mouldboard ploughing operation to a depth of 25-30 cm in October followed by a pass with a field cultivator to a depth of 15 cm. The mouldboard plough consisted of three bottoms of 0.50 m width. The ST treatment consisted of a subsoiler pass to a depth of 25 cm in October followed by a field cultivator to 15 cm depth. The RT treatment was implemented with one or two passes of cultivator to 15 cm depth in October. The subsoiler and the cultivator had the same characteristics as that used in the SV site.

In Peñaflor (PN), two cropping systems were compared: a continuous barley cropping system (PN-CC) and a barley-fallow rotation (PN-CF). In the barley-fallow rotation, both phases of the rotation were represented at the field every season (PN-CF1 and PN-CF2). Three tillage systems were compared at both cropping systems: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). In the PN-CC system, the CT treatment consisted of mouldboard ploughing to a depth of 30-40 cm in November as primary tillage. The mouldboard plough had the same characteristics as that used at AG. The RT treatment was implemented also in November by chisel ploughing to a depth of 25-30 cm. The chisel plough consisted of 5 rigid shanks spaced 20 cm apart and a shank width of 5 cm. In the CT and RT plots, primary tillage was implemented every season in October followed by a pass of a sweep cultivator to a depth of 10-15 cm as secondary tillage. However, in the PN-CF rotation, primary tillage was implemented in March every two seasons during the fallow phase of the rotation and secondary tillage in May with a cultivator pass to a depth of 15-20 cm . In both PN-CC and PN-CF, mouldboard ploughing , in the CT plots, was followed by a pass with a tractor mounted scrubber consisting of a metal beam passed through the soil surface in order to break down large clods.

At the three experimental sites, in the NT treatment no tillage operations were done and for sowing a direct drill planter was used. In this treatment, soil was free of weeds spraying total herbicide (glyphosate).

At all sites, tillage treatments were arranged in a randomized complete block design with three replicates in SV, PN-CC and PN-CF and with four replicates in AG. Plot size was 50x7 m at SV, 50x9 m at AG and 33x10 m at PN-CC and PN-CF.

Soil CO_2 fluxes

After sowing, soil CO_2 emissions were measured every 15 days from December 2002 to June 2005 at the PN site. At the SV and AG sites, measurements were taken once per month from December 2003 to June 2005 with the exception of the short fallow period (July-November 2004) when no measurements were made. Three measurements per plot were taken using an open chamber system (model CFX-1, PPSystems, Hertfordshire, London) connected to an infrared gas analyzer (model EGM-4, PPSystems, Hertfordshire, London). This system was based in the chamber designed by Rayment and Jarvis (1997), which was developed to ensure that atmospheric pressure fluctuations were transferred through to the soil surface. The soil CO_2 flux was calculated from the difference in CO_2 concentration between air entering and leaving the chamber. The chamber has a cylindrical diameter of 21 cm, covering a soil surface of 346 cm^2. Flow rate was adjusted to 900 mL min^{-1}. The chamber was inserted 3 cm into the soil to prevent CO_2 leaks to the atmosphere. The flux readings were taken 3 minutes after the chamber was inserted into the soil in order to avoid possible unrealistic values caused by the disturbance produced after placing the chamber into the soil (Pumpanen et al., 2004).

Daily measurements started at 10:00 am and finished around 12:00 am and were assumed to represent the average flux of the day (Kessavalou et al., 1998). Each plot was divided in two regions and a measurement per region was taken each time. A whole week was used to measure the five experimental fields (one experimental field per day).

C inputs and Weather Data

The inputs of C were computed during three seasons at the PN site (2002-2003, 2003-2004 and 2004-2005) and during two seasons at SV and AG (2003-2004 and 2004-2005). The C inputs consisted of crop straw and dry root biomass at maturity.

After harvest, four soil cores (8 cm diameter x 30 cm depth) per plot (two in the row and the other two in the inter-row) were collected from the top 30 cm of soil in order to measure the root biomass. Once at the laboratory, the soil cores were kept at 4 ºC until root-soil separation. Soil was washed over a 0.5 mm sieve specifically built up for this study in order to remove roots (Böhm, 1979). Roots separated from each soil core were transferred to an aluminium pan and weighed after oven-drying during 48 h at 65 ºC.

Crop straw was measured prior to harvest. Crop plants from four 0.5 m long rows per plot were hand-harvested. The grain was removed from the plant and the straw was oven-dried during 48 h at 65 ºC and weighed. Samples from dry straw and roots were ground and analyzed for C content.

Meteorological data was collected at the three experimental sites over the whole experimental period using automated weather stations and recorded in data-loggers (model CR10, Campbell Scientific Inc.).

Statistical analyses of data were performed using the SAS (SAS Institute, 1990). Analyses of variance (ANOVA) were applied to compare tillage treatments and differences between means were tested with Duncan’s multiple range test.

RESULTS AND DISCUSSION

Weather Conditions and C inputs

During the experimental period, total precipitation recorded was highly variable among and within growing seasons (Table 2). At PN during the 2002-2003 growing season (1 December-31 May) was recorded 244 mm of precipitation. However, in the same site, during the 2004-2005 growing season was recorded 113 mm, with more of the 50% of this rainfall received from April to June (Table 2). At SV and AG, during the 2003-2004 growing season was recorded ≈65% more precipitation than during the 2004-2005 season (Table 2). In the study area, the general rainfall pattern during the growing season was characterized by a specially wet December (i.e., at AG during December 2004 was recorded the 50% of the total precipitation received during the 2004-2005 growing season) followed by a dry winter (i.e. at SV and AG from January to March 2005 was recorded the 14% and 4% of the total precipitation received during the 2004-2005 growing season, respectively) and a wet spring (i.e. at PN during April and May 2005 was recorded the 40% of the total precipitation received during the 2004-2005 growing season). Mean monthly air temperature was similar among sites and growing seasons, varying from 7.8 ºC during the 2003-2004 growing season at SV to 10.4 ºC during the 2002-2003 growing season at PN (Table 2).

The noteworthy rainfall variability led to differences in C inputs among growing seasons (Tables 3 and 4). For example, in the AG site, during the 2003-2004 growing season, the average of C inputs in the four tillage treatments was 4407 kg ha^{-1} (Table 3). However, during the following growing season C inputs dropped to 945 kg ha^{-1} (average of the four tillage treatments (Table 3). As compared with the small grain crop, the greater straw production of the rapeseed crop during the 2004-2005 growing season as compared with a small grain crop led to higher C input and, thus, to lower differences between the 2003-2004 and 2004-2005 growing seasons (Table 3). In PN-CC, C inputs in the 2004-2005 season were a ≈70% lower than in the 2003-2004 season (average of the three tillage treatments) (Table 4). This difference is explained by the different rainfall received during both growing seasons (244 vs. 113 mm in 2003-2004 and 2004-2005, respectively) (Table 2). In semiarid Ebro valley, crop growth and yields are highly dependent on seasonal rainfall as found in previous studies (Cantero-Martínez et al., 1995; Austin et al., 1998; Moret et al., 2007).

Tillage significantly affected C inputs in all the cropping systems and sites studied (Tables 3 and 4). However, differences among tillage treatments were lower than differences among growing seasons. Although, it was not observed a general pattern in the dynamics of C inputs among tillage treatments, during the 2004-2005 growing season, when it was measured the lower precipitation, the greatest C inputs were generally observed under NT (Tables 3 and 4). Working on the same experimental sites, Lampurlanés et al. (2001) and Moret et al. (2006) observed that NT promotes water conservation especially during dry seasons due to the decrease of soil moisture evaporation rates and the better water infiltration in NT compared with CT.

The intensification of the cropping systems produced greater C inputs (Table 4). The inclusion of a fallow phase in the rotation resulted in a crop every two years and, consequently, in a decrease in the C inputs. During the 2002-2003 and 2003-2004 growing seasons the total C input in PN-CC was 7120 kg ha^{-1} (average of the three tillage treatments). However, for the same period of time in the CF rotation C inputs averaged 4451 and 3565 kg ha^{-1} in PN-CF1 and PN-CF2, respectively (Table 4).

Carbon Dioxide Fluxes

Soil carbon dioxide fluxes under different tillage treatments and cropping systems are shown in Figs. 1-3. Emissions of CO_2 were generally less than 2 g CO_2 m^{-2} h^{-1} though higher values were measured during spring 2004 at the three sites (peaks of 2.7, 2.8 and 4.6 g CO_2 m^{-2} h^{-1} at PN-CC, AG and SV respectively) due to the high spring rainfall. From March to May 2004 it was collected 188, 174 and 133 mm of rainfall in SV, AG and PN-CC, respectively (Table 2). This precipitation accounted for more of the 60% of the total precipitation received during the 2003-2004 growing season. Several studies have concluded that rainfall induces soil CO_2 fluxes (Rochette et al., 1991; Akinremi et al., 1999; Parkin and Kaspar, 2004) due to the displacement of the CO_2-rich soil atmosphere produced by water filling the soil pores followed by an increase in microbial activity due to favourable micrometeorological soil conditions for microbial decomposition (Akinremi et al., 1999; Emmerich, 2002). In our study, no relationship was obtained between soil CO_2 flux and surface soil water content (0-5 cm) (data not shown). Low effect of soil water content on soil CO_2 emissions has been also reported by others authors (Hendrix et al., 1988; Frank et al., 2006). At the same time, high rainfall during spring stimulated crop growth leading to a higher root respiration measured by the soil chamber. Unfortunately, the surface chamber methods do not differentiate between heterotrophic-derived CO_2 and root-derived CO_2, limiting the value of these techniques for evaluation of the soil as a source or sink of atmospheric CO_2 (Kuzyakov, 2006).

Generally, annual CO_2 fluxes showed a similar trend for all the sites and cropping systems with low emissions during winter months and an increase in CO_2 fluxes during spring and summer (Figs. 1-3). Low temperatures during winter reduced both heterotrophic and autotrophic respiration. Several studies have concluded that soil temperature is a major factor influencing soil CO_2 emissions (Fortin et al., 1996;

Bajracharya et al., 2000). Frank et al. (2002), in semiarid conditions, observed that the main factor influencing soil CO_2 fluxes was soil temperature accounting for the 65% of CO_2 flux variability. However, in our study, low relationship was found between soil temperature and CO_2 fluxes (R^2 = 0.200-0.400) (data not shown). Soil temperature was only measured to 5 cm depth leading probably to a lack of coincidence between microbial activity and depth of measured soil temperature (Davidson et al., 2000).

Ranges of mean seasonal CO_2 flux were: 0.47-1.76, from 0.45-1.03, 0.20-1.43, 0.10-1.19 and 0.17-0.58 g CO_2 m^{-2} h^{-1} at SV, AG, PN-CC, PN-CF1 and PN-CF2, respectively (Table 5). Although no significant differences in soil CO_2 fluxes were observed among tillage treatments, the lowest mean seasonal fluxes were always observed under NT. As observed in our study, several authors have observed lower seasonal soil CO_2 fluxes in NT compared with CT (Kessavalou et al., 1998; Curtin et al., 2000). Tillage, especially mouldboard ploughing, induces a distribution of the SOM along the soil profile, modifies soil microclimate conditions (e.g. soil temperature, aeration and water content) and exposes aggregate-protected SOM to microbial attack favouring SOM decomposition (Paustian et al., 1997; Peterson et al., 1998). In this study, root respiration has not been measured. However, differences observed in root biomass among tillage treatments (Tables 3 and 4) could indicate that root respiration could have also contributed to the differences in CO_2 flux among tillage treatments.

In contrast to the weak effect of tillage, CO_2 fluxes varied significantly among growing seasons in the three sites (Table 5). This fact is related with the C inputs which were considerably different among growing seasons but similar among tillage treatments (Tables 3 and 4).

Intensification of cropping systems led to an increase in the soil CO_2 fluxes (Table 5). During the 2003-2004 cropping season in PN-CC the seasonal mean CO_2 flux, as average of the three tillage treatments, was 1.36 g CO_2 m^{-2} h^{-1}. The same average calculated in the cropped phase of PN-CF1 was 1.06 g CO_2 m^{-2} h^{-1}. In the same experimental plots, López et al. (2005) observed an 80-90% decrease of the crop residue cover during the fallow phase of the barley-fallow rotation. Consequently, the amount of residues on soil surface during the crop phase of the CF rotation was low. In the CC system, a substantial fraction of residues from the previous crop still remains undecomposed at sowing. As a result, lower soil CO_2 was emitted during the crop phase of the CF rotation compared with the CC system. However, during the 2004-2005 cropping season the suppression of the fallow phase from the rotation did not lead to greater soil CO_2 flux compared with CF (Table 5). The low rainfall registered during the 2004-2005 season (113 mm from December 2004 to June 2005), probably led to a limitation in the activity of the soil microbes and, thus, to lower difference in soil CO_2 between cropping systems. In the CF rotation, greater soil CO_2 flux in the cropped phase than in the fallow phase was attributed to the absence of root respiration during fallow. It is known that fallow leads to a more favourable moisture conditions for microbial decomposition (Grant, 1997; Paustian et al., 2000). However, in our conditions, fallowing is not an efficient practice to increase soil water storage in the study area (Moret et al., 2006).

SUMMARY AND CONCLUSIONS

In semiarid Mediterranean agroecosystems, crop residue production has a strong dependence on seasonal precipitation. In these areas, precipitation is low and highly variable from season to season. Results from this study indicate that variability influenced the amount of C input returned to the soil among in each growing season. On the other hand, C input was less affected by tillage. However, in dry seasons, no-tillage

(NT) lead to slightly greater crop biomass and greater C input into the soil as compared with conventional tillage (CT) due probably to the greater soil water storage. Likewise, soil CO_2 fluxes showed greater differences among cropping seasons than among tillage treatments. As observed with the C input, the greatest soil CO_2 fluxes were measured during cropping seasons with high rainfall. Despite that differences among tillage treatments were in general low, NT always showed the lowest CO_2 fluxes.

Long fallowing in the cereal-fallow rotation led to a decrease in the C input returned into the soil. At the same time, this cropping system reduced soil CO_2 fluxes as measured compared to the continuous cropping mainly because of the absence of root respiration during the fallow phase.

Our results suggest that a move from a CT system to a NT system together with a suppression of the long fallow period from the rotation are suitable practices to increase C inputs to the soil and, at the same time, to reduce soil CO_2 fluxes in semiarid Mediterranean agroecosystems.

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FIGURE CAPTIONS

Figure 1. Soil CO_2 fluxes as influenced by tillage (CT, conventional tillage; ST, subsoiling tillage; RT, reduced tillage; NT, no-tillage) from November 2003 to June 2005 at the Selvanera (SV) and Agramunt (AG) sites. Bars represent LSD (*P* <0.05) for comparison among tillage treatments, where significant differences were found.

Figure 2. Soil CO_2 fluxes as influenced by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) from November 2002 to June 2005 in the continuous cropping system at the Peñaflor site (PN-CC). Bars represent LSD (*P* <0.05) for comparison among tillage treatments, where significant differences were found.

Figure 3. Soil CO_2 fluxes as influenced by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) from November 2002 to June 2005 in the cereal-fallow rotation at the Peñaflor site (PN-CF1 and PN-CF2). Bars represent LSD (*P* <0.05) for comparison among tillage treatments, where significant differences were found.

Table 1. Site and soil characteristics in the Ap soil layer.

Climate and soil characteristics	Study sites			
	Selvanera	Agramunt	Peñaflor	
Latitude	41º 50'N	41º 48'N	41º 44'N	
Longitude	1º 17'E	1º 07'E	0º 46'W	
Elevation (m)	475	330	270	
Soil classification †	Fluventic Xerocrept	Typic Xerofluvent	Xerollic Calciorthid	
Ap horizon depth (cm)	37	28	30	
pH (H_2O, 1:2.5)	8.3	8.5	8.2	
$EC_{1:5}$ (dS m^{-1})	0.16	0.15	0.29	
Water retention (g g^{-1})				
-33 kPa	0.16	0.16	0.20	
-1500 kPa	0.04	0.05	0.11	
Particle size distribution (%)				
Sand (2000-50 µm)	36.5	30.1	32.4	
Silt (50-2 µm)	46.4	51.9	45.5	
Clay (< 2 µm)	17.1	17.9	22.2	
SOC (0-20 cm; g m^{-2})				
No-tillage (NT)	2942	3111	2743‡	2306§
Reduced tillage (RT)	–	2876	2285	2154
Subsoil tillage (ST)	2947	2592	–	–
Conventional tillage (CT)	2869	2541	2278	2021

† Soil classification according to the USDA classification (Soil Survey Staff, 1975).

‡ SOC in PN-CC (Peñaflor site under continuous cropping system).

§ SOC in PN-CF (Peñaflor site under cereal-fallow rotation)

Table 2. Total monthly precipitation (P) and mean monthly air temperature (T) recorded the study period in the three experimental sites.

	Selvanera						Agramunt						Peñaflor							
	2003		2004		2005		2003		2004		2005		2002		2003		2004		2005	
	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)
January	17.2	2.8	2.9	4.9	0.0	0.6	17.6	2.9	5.7	5.0	0.5	1.2	22.2	6.7	31.5	5.8	10.3	7.6	2.4	3.6
February	58.3	0.8	44.2	3.7	5.2	2.4	69.5	4.8	42.6	4.4	1.3	3.0	6.1	9.0	41.0	6.0	43.4	4.7	6.9	4.2
March	8.1	9.6	39.3	7.0	9.0	10.0	21.9	0.0	46.8	7.7	1.5	9.1	48.1	11.8	37.0	11.0	56.4	7.9	7.3	9.6
April	15.5	11.8	65.7	10.4	11.3	12.5	19.6	13.3	60.6	11.1	2.3	13.6	27.1	13.1	31.9	13.4	42.0	11.2	15.6	13.7
May	37.7	16.8	82.8	16.6	44.3	18.3	46.3	17.6	66.8	16.0	8.1	19.1	72.5	16.1	69.1	17.5	34.9	15.9	48.5	18.4
June	11.0	24.6	15.0	23.2	30.4	23.6	1.7	26.2	18.4	22.9	1.0	24.3	40.4	23.0	27.1	25.6	5.9	23.6	45.0	23.8
July	20.2	25.0	52.9	24.1	1.9	27.2	4.5	26.4	27.9	24.0	0.2	25.6	17.3	23.4	0.6	25.9	14.5	23.9	0.2	24.8
August	12.0	26.2	37.5	24.4	27.9	22.6	12.3	27.9	22.2	24.5	4.7	23.0	8.5	22.8	10.3	26.9	10.5	24.2	4.0	23.3
September	140.7	19.0	21.5	23.8	50.4	26.0	110.3	19.4	0.8	20.9	3.5	19.2	59.6	19.0	65.9	19.6	25.3	21.1	28.9	19.9
October	93.7	13.1	22.5	24.5	54.2	15.7	107.1	12.8	23.0	14.4	69.6	15.3	53.9	15.3	61.4	14.2	32.9	16.6	46.1	15.9
November	33.6	8.8	3.2	14.5	43.4	7.9	46.0	8.8	2.7	6.0	61.6	7.4	14.5	11.3	47.9	9.9	8.5	7.7	22.4	8.8
December	48.5	4.4	33.4	4.6	9.5	0.1	42.9	4.9	40.5	4.7	8.3	3.9	33.5	8.7	18.6	6.6	32.7	6.8	9.3	3.0
Year	*496*	*13.6*	*421*	*15.1*	*288*	*13.9*	*500*	*13.7*	*358*	*13.5*	*163*	*13.7*	*404*	*15.0*	*442*	*15.2*	*317*	*14.3*	*237*	*14.1*

Table 3. Effects of tillage on crop biomass production and C inputs for different growing seasons at the Agramunt (AG) and Selvanera (SV) sites.

Site	Tillage†	Crop	Grain yield	Straw yield	Root biomass	C inputs§
				kg ha^{-1}		
			2003-2004			
SV	CT	Wheat	2703a‡	11693a	1490b	5858a
SV	ST	Wheat	2363a	10616ab	1806a	5500ab
SV	RT	Wheat	1830b	9061b	1313b	4603b
SV	NT	Wheat	2454a	9320b	1799a	4914b
AG	CT	Barley	3558a	8970a	1130ab	4489a
AG	ST	Barley	3605a	8975a	1416a	4605a
AG	RT	Barley	3320a	8471a	1009ab	4216a
AG	NT	Barley	3699a	9575a	923b	4678a
			2004-2005			
SV	CT	Rapeseed	1261b	4440b	2921b	3166b
SV	ST	Rapeseed	1565ab	4860ab	3399b	3547ab
SV	RT	Rapeseed	1783a	5229a	4117ab	4000a
SV	NT	Rapeseed	1462ab	4105b	5864a	4193a
AG	CT	Wheat	798b	911c	600c	650c
AG	ST	Wheat	925a	1667a	1168b	1217a
AG	RT	Wheat	911a	1192b	941b	913ab
AG	NT	Wheat	792b	984c	1395a	1001ab

† CT, conventional tillage; ST, subsoiling tillage; RT, reduced tillage; NT, no-tillage.

‡ Different letters indicate significant differences among tillage treatments within the same site and growing season (P<0.05).

§Assuming 45% of C in straw and 40% in roots.

Table 4. Effects of tillage and cropping system on crop biomass production and C inputs for different growing seasons at the Peñaflor site.

Cropping system†	Tillage‡	Crop	Grain yield	Straw yield	Roots	C inputs¶
				kg ha^{-1}		
			2002-2003			
PN-CC	CT	Barley	2493a§	5741a	1436b	3158a
PN-CC	RT	Barley	2273b	4674b	1452b	2684b
PN-CC	NT	Barley	1976c	4742b	1793a	2851b
PN-CF1	CT	Fallow	0	0	0	0
PN-CF1	RT	Fallow	0	0	0	0
PN-CF1	NT	Fallow	0	0	0	0
PN-CF2	CT	Barley	3133a	6479a	1620b	3564ab
PN-CF2	RT	Barley	3373a	6688a	2077a	3840a
PN-CF2	NT	Barley	2426b	5465b	2078a	3290b
			2003-2004			
PN-CC	CT	Barley	3514a	8469a	871b	4159b
PN-CC	RT	Barley	3071b	8233a	931b	4077b
PN-CC	NT	Barley	3083b	8850a	1127a	4433a
PN-CF1	CT	Barley	3518ab	8907a	916b	4375b
PN-CF1	RT	Barley	3721a	9272a	1270a	4680a
PN-CF1	NT	Barley	3311b	8735a	919b	4298b
PN-CF2	CT	Fallow	0	0	0	0
PN-CF2	RT	Fallow	0	0	0	0
PN-CF2	NT	Fallow	0	0	0	0
			2004-2005			
PN-CC	CT	Barley	331a	1377a	1510b	1224b
PN-CC	RT	Barley	313a	1203a	1860b	1285b
PN-CC	NT	Barley	228a	828b	2650a	1433a
PN-CF1	CT	Fallow	0	0	0	0
PN-CF1	RT	Fallow	0	0	0	0
PN-CF1	NT	Fallow	0	0	0	0
PN-CF2	CT	Barley	1314a	2861a	3144b	2545b
PN-CF2	RT	Barley	1086ab	2579ab	3968b	2748b
PN-CF2	NT	Barley	730b	2039b	6577a	3548a

† PN-CC, continuous cropping; PN-CF1 and PN-CF2, cereal-fallow rotation.

‡ CT, conventional tillage; RT, reduced tillage; NT, no-tillage.

§Different letters indicate significant differences among tillage treatments within the same cropping system and growing season (P<0.05).

¶Assuming 45% of C in straw and 40% in roots.

Table 5. Effect of tillage and cropping system on mean soil CO_2 fluxes during different cropping seasons at the three experimental sites.

Site‡	Cropping season	Crop	Tillage treatment†		
			NT	RT	CT
				g CO_2 m^{-2} h^{-1}	
SV	2003-2004	Wheat	1.56aA§	1.65aA	1.76aA
	2004-2005	Rapeseed	0.47aB	0.55aB	0.47aB
AG	2003-2004	Barley	0.87aA	0.92aA	1.03aA
	2004-2005	Wheat	0.45aB	0.45aB	0.51aB
PN-CC	2002-2003	Barley	0.20aB	0.23aB	0.24aB
	2003-2004	Barley	1.23aA	1.43aA	1.42aA
	2004-2005	Barley	0.39bB	0.56aB	0.58aB
PN-CF1	2002-2003	Fallow	0.10aB	0.11aB	0.12aB
	2003-2004	Barley	0.85bA	1.13aA	1.19aA
	2004-2005	Fallow	0.27bB	0.41abB	0.54aB
PN-CF2	2002-2003	Barley	0.17aB	0.19aB	0.19aB
	2003-2004	Fallow	0.41aA	0.49aA	0.58aA
	2004-2005	Barley	0.41aA	0.58aA	0.52aA

† CT, conventional tillage; ST, subsoiling tillage; RT, reduced tillage; NT, no-tillage

‡ SV, Selvanera; AG, Agramunt; PN-CC, continuous cropping at Peñaflor; PN-CF1 and PN-CF2, cereal-fallow rotation at Peñaflor.

§ Different lower case letters indicate significant differences among tillage treatments within the same site and growing system (P <0.05). Different upper case letters indicate significant differences among growing seasons within the same tillage treatment and site (P <0.05).

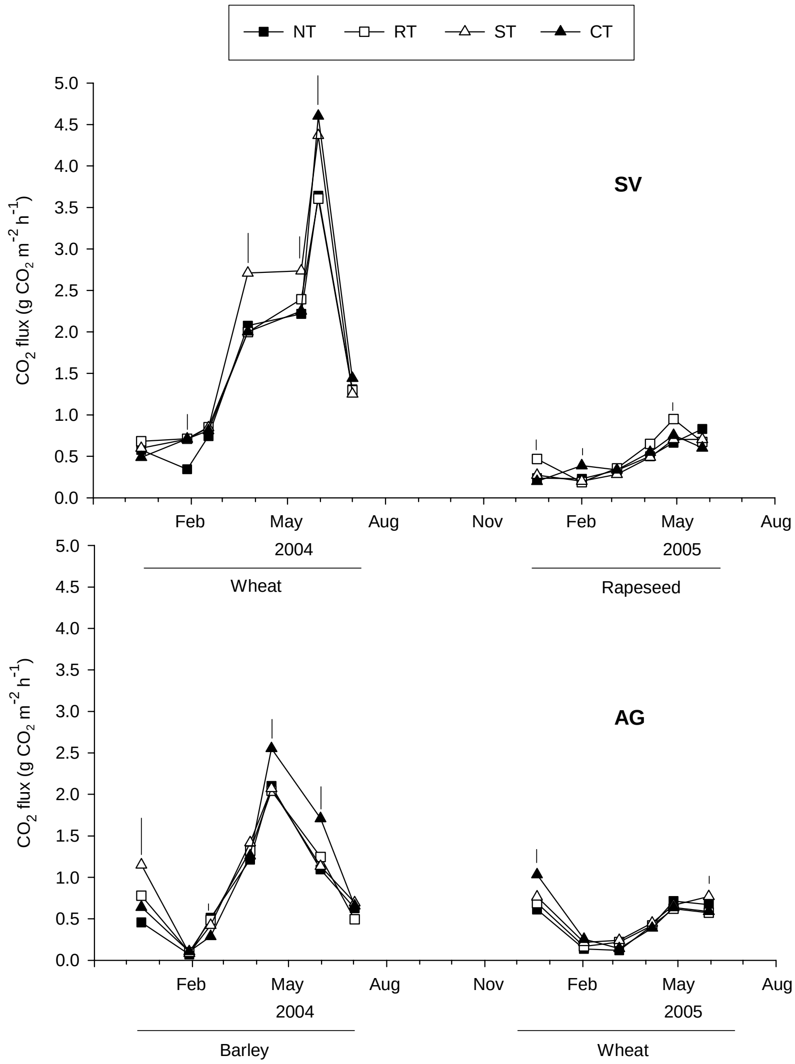
NT
RT
ST
CT
SV
AG
CO2 flux (g CO2 m-2 h-1)
Feb
May
Aug
Nov
2004
2005
Wheat
Rapeseed
Barley
Wheat

Fig. 1.

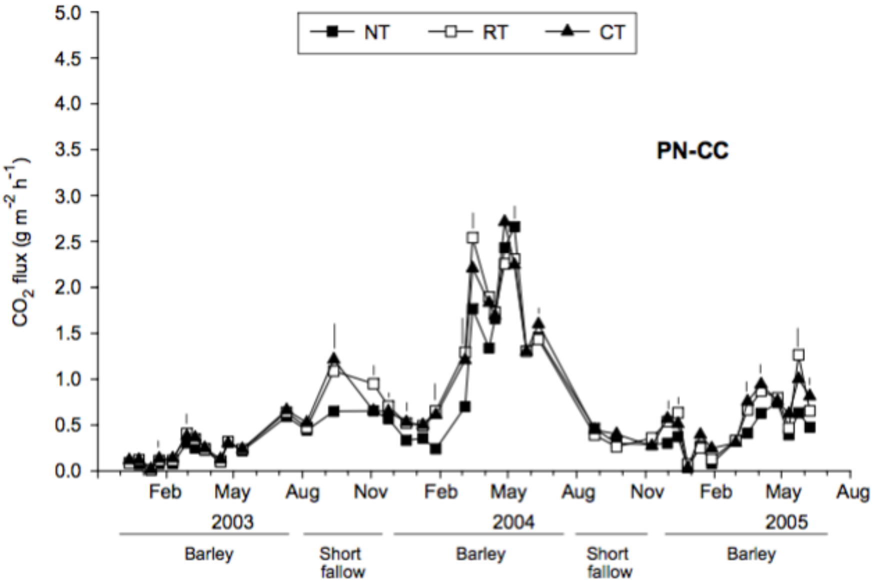
NT
RT
CT
PN-CC
CO_2 flux (g m^{-2} h^{-1})
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Feb May Aug Nov Feb May Aug Nov Feb May Aug
2003
2004
2005
Barley
Short fallow
Barley
Short fallow
Barley

Fig. 2.

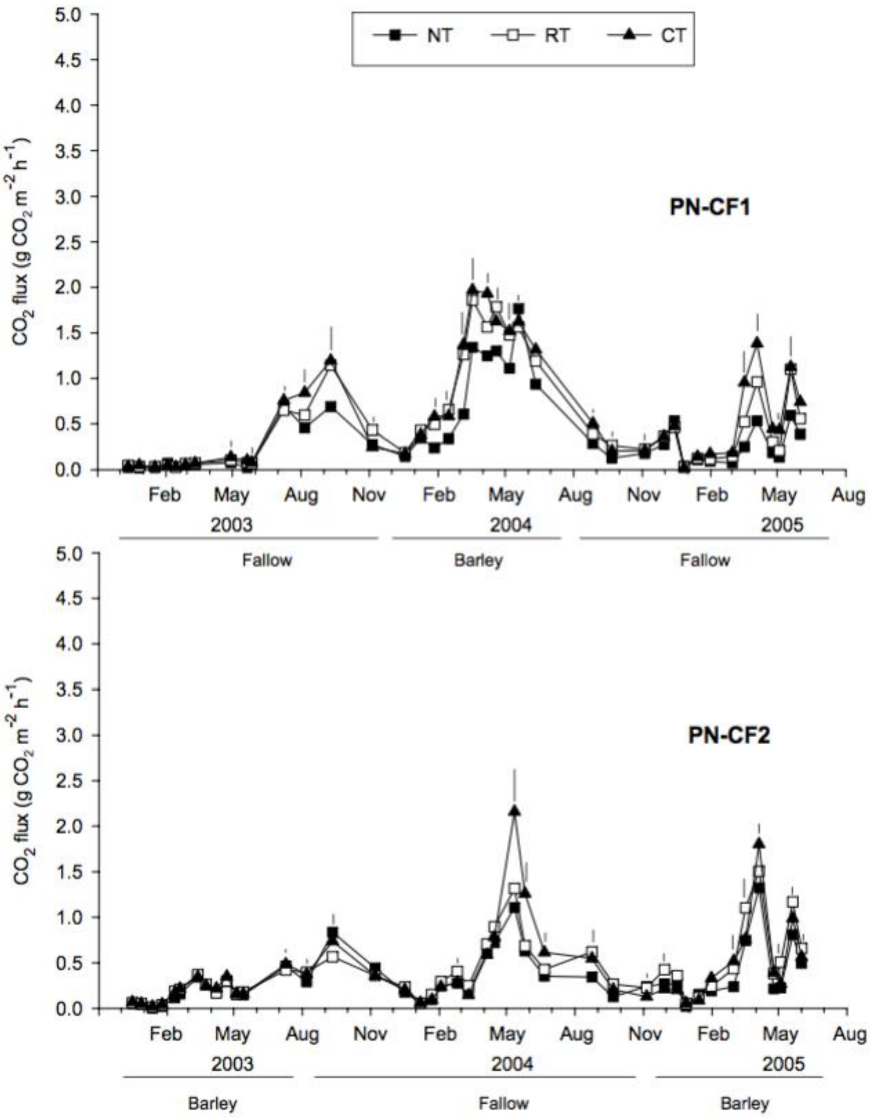
NT
RT
CT
PN-CF1
CO2 flux (g CO2 m-2 h-1)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Feb May Aug Nov Feb May Aug Nov Feb May Aug
2003
2004
2005
Fallow
Barley
Fallow
PN-CF2
CO2 flux (g CO2 m-2 h-1)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Feb May Aug Nov Feb May Aug Nov Feb May Aug
2003
2004
2005
Barley
Fallow
Barley

Fig. 3.